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Study on the Impact of National Value Chain Embeddings on the Embodied Carbon Emissions of Chinese Provinces

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Abstract: Accelerating the construction and optimization of national value chains is of great significance to reducing both pollution and carbon emissions and promoting green economic growth. In accordance with the input–output table and carbon emission statistics of China in 2012, 2015, and 2017, in this paper, we use the total trade decomposition method and the value chain decomposition method to decompose the embodied carbon emissions and the embeddedness of national value chains. Subsequently, we empirically study, for the first time, the impact of the degree of domestic value chain embedding on implicit carbon emissions using the calculated results. The results show the following: (1) The top three provinces with embodied carbon emissions are Shandong, Hebei, and Jiangsu, while the top four industries are the production and supply of electricity and heat; metal smelting and rolling processing; non-metallic mineral products; and transportation, warehousing, and postal services. (2) The degree of forward and backward national value chain embeddedness in Chinese provinces has increased, and the degree of forward embeddedness in most provinces and industries is lower than that of backward embeddedness. (3) The embeddedness of domestic value chains and embodied carbon emissions is always negatively correlated, and this conclusion is still valid after robustness and endogeneity tests. (4) There is industrial heterogeneity in the impact of the degree of embeddedness of domestic value chains on embodied carbon emissions.

Keywords: embodied carbon emissions; embeddedness of national value chains; input–output model; reference regression; industrial heterogeneity

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1. Introduction

Since the 14th Five-Year Plan period, China has started on a new path toward constructing a modern socialist nation. Achieving the carbon peak and neutrality on time has become the agreed path and an inevitable decision in order to foster high-quality economic and social development and expedite the building of a green civilization.

As is known to all, the division of labor is a hot topic within the current context of the global economy. The international and domestic division of labor are the embodiment of the continuous optimization of resource allocation in the process of commodity production. With improvements in the international and local division of the labor system, the connection between the level of embeddedness and carbon emissions between countries and industries has become more complex. The United Nations Framework Convention on Climate Change defines embodied carbon as “the CO_2 emitted from the source, manufacture, processing and transport of raw materials to the purchase of the product by the consumer”. Implicit carbon trade and added value trade refer to the transfer and flow of CO_2 and added value caused by trade activities such as goods and services between regions. Driven by both the global value chain and the domestic value chain, the production of products increasingly shows the characteristics of cross-border and cross-regional cooperation, and countries and regions integrate into the global production network according to their comparative advantages. This trend not only promotes the global reallocation of production factors, but also triggers the transnational flow of hidden carbon trade, which brings a new situation of both opportunities and challenges for countries to reduce pollution and carbon. Therefore, an in-depth understanding of the hidden carbon emissions of various provinces and industries in China is conducive to realizing the synergies of carbon reduction and pollution reduction at an early date and promoting the sustainable and stable growth in the green economy.

2. The Environmental Impact of Global Value Chain Embeddedness

In order to systematically examine the internal relationship between value chains and the environment, some articles have focused on the role of the global value chain position and embeddedness on the economy and the environment. Ji et al. [1] argued that different modes of participation in global value chains can lead to disparities in the environmental costs of international trade, resulting in inequalities among trading economies. Research by Jithin and Sania confirmed this, showing that global value chain embedding is positively correlated with CO_2 emissions in developing economies, but it has a suppressive effect on high-growth economies. Additionally, forward participation in global value chains has varying impacts on CO_2 emissions, while backward participation reduces CO_2 emissions in both developing and developed economies [2]. Lv et al. [3], based on the global multi-regional input–output model and the panel smooth transformation model, found that global value chain engagement has a non-linear impact on the exports and imports of implicit carbon, the trade carbon balance, and pollution in terms of trade. Zheng et al. [4] confirmed the view of Lv et al. [3]. In the course of studying the implications of global value chain participation for the embodied carbon emissions of Chinese exports, it was found that the improvement of the position of GVCs led to an inverted U-shaped distribution of the implied carbon exports from China. With the long-term development of the green low-carbon cycle system, China has entered a high-quality development stage of lowering carbon emissions, and the dual-carbon goal has become an important engine to break through the constraints of resources and the environment, and achieve sustainable development. Some scholars have re-evaluated the implied emission characteristics of China's international commerce and found that China's implied emission exports are mainly focused on manufacturing and take simple global value chain routes, while exports through complex global value chains tend to be resource inputs. Improving the position of global value chains and optimizing the bilateral commerce structure between China and other countries are conducive to achieving global emission reduction targets [5]. In view of the urgent economic and ecological environment situation, many scholars have explored the causes of carbon emissions in great depth and proposed corresponding solutions for China to achieve its dual-carbon target. Guo et al. [6] found that using renewable energy mitigates the detrimental effects of the worldwide value chain division of the labor system on the balance of carbon emissions. Wang et al. [7] studied the dynamic correlation between global value chain participation, CO_2 emissions, and economic growth, and found that raising the GDP per person and decreasing the CO_2 emissions per person can promote global value chain participation and help realize environmentally friendly growth at an early date.

3. Environmental Impact of Different Participation Models in Global Value Chains

As the world's division of labor and globalization have continued to expand, the transformation of countries' participation in global value chains has increasingly complicated their impacts on economic development, resources, and the environment. Previous studies have confirmed that the forward correlation and backward correlation in the global value chains have varying effects on the correlation between carbon emissions and exports in various industries and geographic areas. Consequently, examining the relationship between different participation modes of global value chains (forward embeddedness and backward embeddedness) and trade-induced ecological exchange inequality is of paramount importance. Ji et al. [1] showed that positive linkage participation in global value chains can greatly decrease local energy consumption per unit of value added, while reverse interconnected participation may increase energy consumption per unit of value added, indicating that trade is a key driver of energy inequality. Qian et al. [8] analyzed in detail the mechanism of positive and reverse participation in GVCs on CO_2 emissions and found that increasing positive participation in global value chains can reduce CO_2 emissions, while increasing reverse participation can increase CO_2 emissions at the country level. Positive participation in global value chains reduces emissions by advancing industrial technologies, and reverse participation raises emissions by expanding trade. Laiet al. [9] argued that improving the GVCs′ forward division of labor will encourage the "inflection point" of the environmental Kuznets curve (EKC) to arrive sooner rather than later, while the GVCs′ backward division of labor will cause the "inflection point" of the environmental Kuznets curve (EKC) to arrive much later. Zhu et al. [10] argued that there exists a positive spatial dependence among nations and that forward and backward participation in global value chains have different spatial spillover effects, with the backward spillover effect being the largest.

4. The Environmental Impact of the Degree of National Value Chain Embeddedness

With the accelerated expansion of GVCs and the continuous improvement of the national regional economy, China's core status in the worldwide network division of labor is increasingly prominent, as is the position of national value chains. This development holds profound implications for the harmonious coexistence and advancement of China's economy and environment. Sun et al. found that the carbon emission efficiency of Chinese cities is generally low and presents a "ladder" distribution from coastal to inland, and the difference in carbon emission efficiency shows a trend of decreasing first and then increasing, with the interregional gap being the key to narrowing the overall gap in the future [11]. Chen and Li [12] studied the vertical division of labor and the horizontal division of labor in domestic value chains, and found that the vertical division of labor can narrow the provincial–industry carbon emission intensity gap, while the horizontal division of labor will widen the provincial–industry carbon emission intensity gap, and the vertical division of labor has a stronger effect than the horizontal division of labor. Comprehensively weighing the financial advantages and emission costs of China's involvement in both local and global value chains and striving to realize the mutual benefits of dual value chain upgrading and the establishment of a low-carbon economy are key issues for China. Bai et al., according to the connection between local and global value chains, found that traditional value chain trade has a significant impact on China's environment and employment, and simple value chain trade linked to global value chains reduces global employment and emissions, while complex value chain trade associated with global value chains has the opposite effect [13].

5. Application of Multi-Regional Input–Output Model

As a powerful analytical tool, the multi-regional input–output model can capture the cross-regional flow of goods and services in the process of production and consumption and the resulting transfer of carbon emissions. Shen compared traditional trade and value-added trade accounting methods and found that it was more scientific and reasonable to calculate the implied carbon emissions in China's foreign trade by using the MRIO model and total trade decomposition method [14]. By comparison, although life cycle assessment (LCA) has advantages in assessing the environmental impact of the whole life cycle of products, it is weak in dealing with the transfer of carbon emissions in complex economic systems. Although the structural equation model (SEM) can reveal the complex relationship between variables, it is not able to quantify the hidden carbon emission. Taking into account research objectives, data accessibility, computing resources, and model applicability, multi-regional input–output models still have irreplaceable advantages in revealing the dynamics of carbon emissions in global or national value chains and promoting synergies in carbon reduction and pollution reduction.

The studies mentioned above indicate that the current research on how global value chains affect the economy and environment is now at a mature stage. Existing studies have mainly explored the relationship between global value chains and hidden carbon emissions at the national level from an international perspective, while few papers have conducted detailed studies at the provincial level. Therefore, the innovation of this study lies in its initial examination of national value chains from industry and province viewpoints, as well as its first-ever investigation of national value chains' influence on embodied carbon emissions. This study's primary contribution is as follows: the total trade decomposition method is used to calculate the hidden carbon emissions of domestic provinces (industries), and the multi-regional input–output table of China is used to calculate the forward and backward embeddedness of domestic value chains. Considering the computed outcomes, fixed-effect regression is carried out on the degree of embeddedness of domestic value chains and the implied carbon emissions, and the conclusion is that the degree of embeddedness of domestic value chains has an adverse correlation with the implied carbon emissions. Robustness and endogeneity tests were carried out on this conclusion, and regression analysis remained consistent from the perspective of industrial heterogeneity. This research endeavor fills a gap in the domestic research and provides a realistic basis for the green growth of the domestic economy.

6. National Value Chain Embeddedness and Measurements of Region–Industry Embodied Carbon Emissions

6.1. Measurement and Analysis of National Value Chain Embeddedness

National Value Chain Measurement Methods

Domestic value chains are modern industrial chains with a complete system, close correlation, and strong competitiveness based on domestic market demand, relying on the resource allocation of various regions in China, and maximizing the comparative advantages of various regions.

This paper depends on the measurement method of the value chain adopted by Wang et al. [15] and Lv et al. [3]. The added value of national departments is divided into five parts according to the destination. It is known that China's multi-regional input–output table includes G provinces and N industrial sectors, where V^s is the added value of N departments in s province (order $1 \times N$), $\hat{V}^S$ is the added value coefficient vector (order $N \times 1$), and L^{ss} is the Leontief inverse matrix (order $N \times N$) of region s. A^{sr} and A^{st} are the nth-order intermediate demand coefficient matrices of region s to region r and region s to region t, respectively. B^{ru} and B^{tu} are the block matrices of the Leontief inverse matrix (order $N \times N$). Y^{ss}, Y^{rr}, and Y^{sr} are the column vectors of the final demand of region s itself, region r itself, and region s for N industrial sectors of region r, respectively (Y^{us}, Y^{ur}, etc.).

The added value of national departments is decomposed forward, and the decomposition formula is as follows:

$$(V^s)' = \underbrace{\hat{V}^s L^{ss} Y^{ss}}_{V-D} + \underbrace{\hat{V}^s L^{ss} \sum_{r \neq s}^{G} Y^{sr}}_{V-RT} + \underbrace{\hat{V}^s L^{ss} \sum_{r \neq s}^{G} A^{sr} L^{rr} Y^{rr}}_{V_{NVC}-R} + \underbrace{\hat{V}^s L^{ss} \sum_{r \neq s}^{G} A^{sr} \sum_{t}^{G} B^{rt} Y^{ts}}_{V_{NVC}-D} + \underbrace{\left[\hat{V}^s L^{ss} \sum_{r \neq s}^{G} A^{sr} \sum_{t}^{G} \left(B^{rt} \sum_{u \neq s}^{G} Y^{tu} \right) - \hat{V}^s L^{ss} \sum_{r \neq s}^{G} A^{sr} L^{rr} Y^{rr} \right]}_{V_{NVC}-FV} \tag{1}$$

Formula (1) divides the added value of national departments into five parts, with specific meanings as follows: *V-D* is the value added to meet the local final demand; *V-RT* is the value added hidden in the final requirement exported to other regions; V_{NVC}-*R* is the value added hidden in the intermediary goods exported to other regions and returned to the local market to satisfy the local final demand; V_{NVC}-*D* is the value added hidden in the intermediate products exported to other regions and used to meet the local final demand; and V_{NVC}-*FV* is value added implied in intermediate goods that are re-exported to other regions from the place of import.

Similarly, the final product at the national sector level is decomposed backward, and the decomposition formula is as follows:

$$(Y^s)' = \underbrace{\hat{V}^s L^{ss} Y^{ss}}_{Y-D} + \underbrace{\hat{V}^s L^{ss} \sum_{r \neq s}^{G} Y^{sr}}_{Y-RT} + \underbrace{\sum_{r \neq s}^{G} V^r L^{rr} A^{rs} L^{ss} Y^{ss}}_{Y_{NVC}-R} + \underbrace{\hat{V}^s \sum_{r \neq s}^{G} B^{sr} A^{rs} L^{ss} \sum_{t}^{G} Y^{st}}_{Y_{NVC}-D} + \underbrace{\left[\sum_{r \neq s}^{G} V^r \sum_{t \neq r}^{G} B^{rt} A^{ts} L^{ss} \sum_{u}^{G} Y^{su} - \sum_{r \neq s}^{G} V^r L^{rr} A^{rs} L^{ss} Y^{ss} \right]}_{Y_{NVC}-FV} \quad (2)$$

Formula (2) also divides the final product at the national sector level into five parts, with specific meanings as follows: *Y-D* is the added value used to satisfy the local demand for final products; *Y-RT* is the local added value used to meet end-product requirements in other regions; Y_{NVC}-*R* is the added value of other regions implicit in the import of intermediate products; Y_{NVC}-*D* is the local added value implied in the import of intermediate goods; and Y_{NVC}-*FV* is the added value implied in the third region of the import of intermediary goods.

According to the formula for the forward decomposition of added value and backward decomposition of the final product, the degree of embeddedness of domestic value chains forward and backward can be obtained as follows:

Forward embeddedness of national value chains:

$$NVCf = (V_{NVC} - R) / (V^s)' + (V_{NVC} - D\Big) / (V^s)' + (V_{NVC} - FV\Big) / (V^s)' \quad (3)$$

Backward national value chain embeddedness:

$$NVCb = (Y_{NVC} - R) / (Y^s)' + (Y_{NVC} - D\Big) / (Y^s)' + (Y_{NVC} - FV) / (Y^s)' \quad (4)$$

Therefore, as a node in the domestic geographic division of the labor network system, the greater the forward embeddedness of a district in a national value chain, the closer it is to the upstream segment of the value chain. Conversely, with higher the backward embeddedness, the closer the node to low-value-added production links. The ratio of domestic value chain embeddedness based on forward correlation to domestic value chain embeddedness based on backward correlation is defined as the degree of domestic value chain embeddedness, that is, *NVC*. The larger the value, the more a region is at the top of the value chain with technological advantages. The formula is as follows:

$$NVC = NVCf / NVCb \quad (5)$$

7. Analysis of the Results of Domestic Value Chain Measurement for Each Province and Industry in China

Through the above methods, we calculated the domestic value chain embeddedness based on forward correlation and domestic value chain embeddedness based on backward correlation in each Chinese province, and the outcomes are displayed in Figure 1. In 2012, 2015, and 2017, China's provinces have increased the embeddedness of forward and backward domestic value chains, which is rooted in the in-depth implementation of regional economic integration strategies and industrial upgrading policies promoted at the national level. These policies not only promote close cooperation between upstream and downstream enterprises in the industrial chain, but also accelerate technological innovation and efficient allocation of resources, thus promoting the all-round embeddedness of provinces in the domestic value chain. Specifically, the improvement of forward correlation embeddedness reflects the increasing participation of various provinces in high-end links such as technological innovation, product research, and development and brand building, which not only improves the overall competitiveness of the industrial chain, but also promotes the transformation of the industrial structure in a more high-end and intelligent direction. The growth in correlation embeddedness reveals the continuous optimization of synergies among provinces in basic links such as raw material procurement, parts production, and logistics distribution, further consolidating the stability and efficiency of the supply chain. The degree of forward embeddedness is lower than that of backward embeddedness in most provinces, such as Zhejiang, Liaoning, Guizhou, and Gansu, demonstrating that the majority of provinces continue to be at the bottom of the value chain. The high output value links, such as a supply of raw materials, product development and design, and scientific and technological innovation, represented by the forward embeddedness of domestic value chains, are mainly concentrated in regions with good economic development, such as Beijing and Shanghai. Low value-added links such as processing, manufacturing, and assembly, represented by the backward embeddedness of domestic value chains, are mainly concentrated in areas with less developed economies, such as Anhui, Chongqing, and Ningxia.

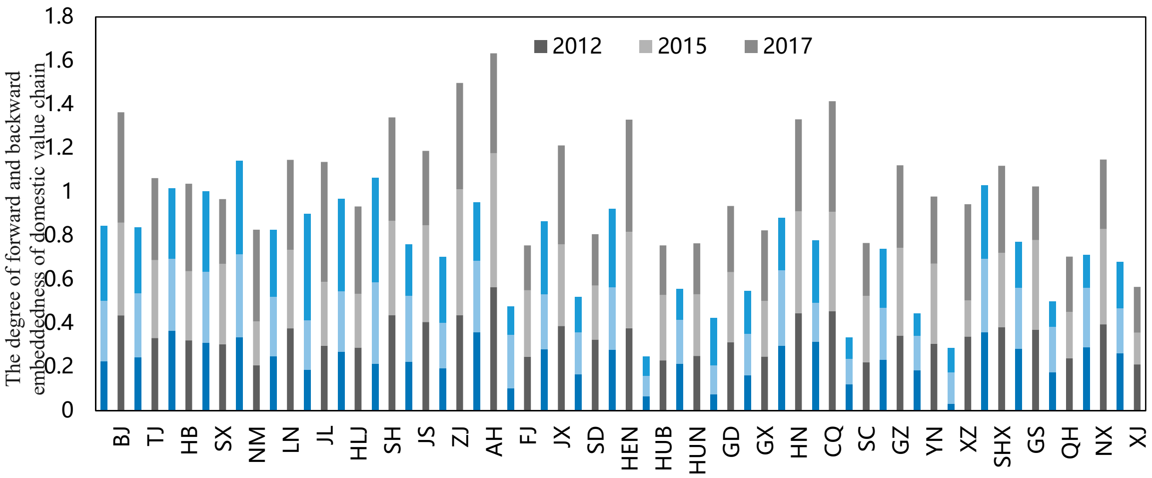


Figure 1. The degree of forward and backward embeddedness of national value chains in Chinese provinces in 2012, 2015, and 2017. Note: The first column (blue bars) in the bar chart for each province is the degree of forward NVC embeddedness, and the second (gray bars) is the degree of backward NVC embeddedness. The horizontal axis provides the English abbreviation of each province, corresponding to "Beijing" and other provinces in Table 1.

Table 1. Total embodied carbon emissions by province in China.

Province	Total Carbon Emission/Megaton		
	2012	2015	2017
Beijing (BJ)	83.2893	76.0397	68.9398
Tianjin (TJ)	153.6335	146.4253	135.5043
Hebei (HB)	723.2272	748.8310	751.8373
Shanxi (SX)	481.5651	444.9931	491.7388
Inner Mongolia (NM)	609.6059	592.9270	644.6625
Liaoning (LN)	466.4838	477.8475	479.1956
Jilin (JL)	223.8702	223.1426	198.2456
Heilongjiang (HLJ)	263.1492	263.4798	267.3971
Shanghai (SH)	185.5815	182.9412	183.0973
Jiangsu (JS)	641.8361	704.7714	738.9094
Zhejiang (ZJ)	365.9317	361.0118	366.8463
Anhui (AH)	316.3817	350.1703	367.2074
Fujian (FJ)	227.4092	228.9282	229.1293
Jiangxi (JX)	160.9821	208.7144	220.5879
Shandong (SD)	842.4372	826.0398	804.8447
Henan (HEN)	504.2974	508.5358	480.7885
Hubei (HUB)	361.9209	298.5528	312.4743
Hunan (HUN)	276.9255	274.1067	304.2400
Guangdong (GD)	482.5639	479.4533	515.5789
Guangxi (GX)	201.1097	196.7773	222.0241
Hainan (HN)	36.2130	40.9746	40.7099
Chongqing (CQ)	162.4388	155.3400	151.4783
Sichuan (SC)	312.3185	309.4937	295.3597

Table 1. *Cont.*

Province	Total Carbon Emission/Megaton		
	2012	2015	2017
Guizhou (GZ)	218.4025	222.1945	240.4803
Yunnan (YN)	206.4377	170.6261	188.5501
Xizang (XZ)	2.5567	3.9816	4.6196
Shaanxi (SHX)	254.8751	271.7839	262.4968
Gansu (GS)	145.9931	151.8592	142.8504
Qinghai (QH)	42.1053	48.3108	50.0691
Ningxia (NX)	135.0127	140.2689	176.7519
Xinjiang (XJ)	250.0589	336.7672	393.6182

From the perspective of industrial heterogeneity, in this paper, we calculate the annual average for the forward and backward domestic value chain embeddedness of different industries in China in 2012, 2015, and 2017, as shown in Figure 2. The graphic illustrates that the backward embeddedness of the domestic value chain in various industries is notably higher than the forward embeddedness, suggesting that most industries are still at the bottom of the value chain, especially the chemical product industry, electronic and communication equipment industry, and other high-tech industries, which have a large gap between their forward and backward embeddedness, indicating that China needs to vigorously strengthen the practice of scientific and technological innovation. Businesses with high forward and backward embeddings are mainly concentrated in the oil and gas mining industry, the coal mining products industry, and the metal mining products industry in the manufacturing industry, with values as follows: forward: 0.81, 0.65, and 0.58, respectively; and backward: 0.90, 0.81, and 0.73, respectively. This indicates that these industries have made some achievements in raw material supply, technological innovation, etc., while still not removing the low-end effect-locking impact.

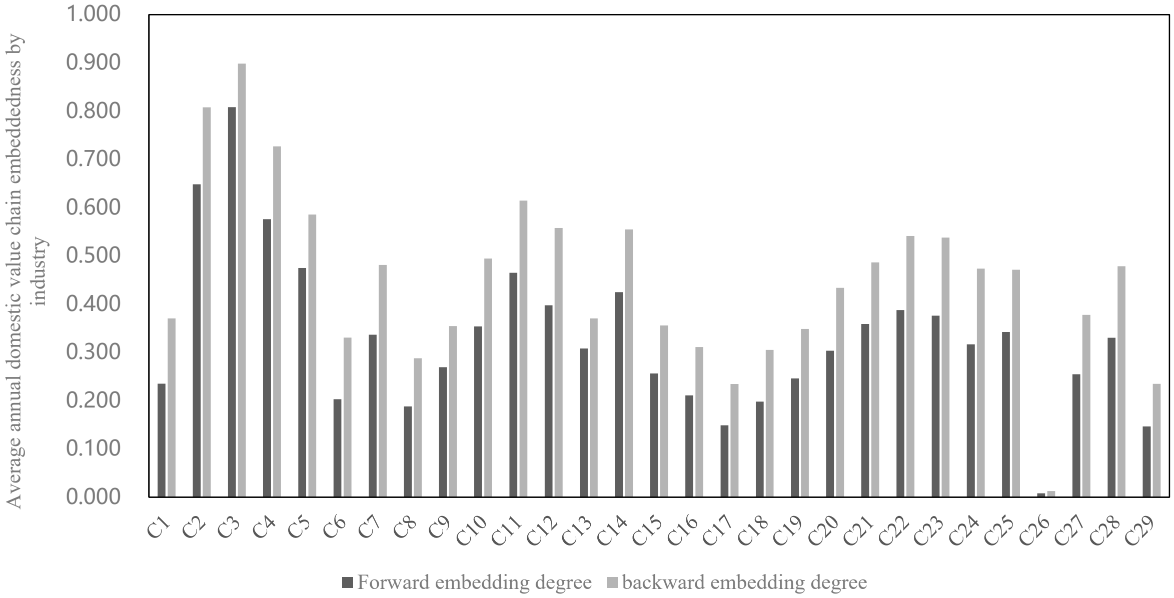


Figure 2. The annual average degree of embeddedness of China's national value chains in 2012, 2015, and 2017. Note: C1–C29 of the horizontal axis correspond to industries such as "agriculture, forestry, animal husbandry and fishery" in Table 2.

Table 2. Total embodied carbon emissions of various industries in China.

Industry	Total Carbon Emissions/Megaton		
	2012	2015	2017
Agriculture, forestry, animal husbandry and fisheries	130.4960	130.6411	139.4403
Coal extraction products	298.6843	267.5523	253.4375
Oil and gas extraction	53.1592	50.8315	42.9667
Metal mining products	21.4038	19.7489	15.2226
Mining of non-metallic and other minerals	15.7835	11.7912	8.1470
Food and tobacco	60.7594	48.0418	48.0434
Textiles	22.5867	19.7111	14.9966
Textiles, clothing, shoes, hats, leather, down and articles thereof	7.0931	5.9817	4.9468
Woodwork and furniture	9.0266	6.8554	6.2124
Paper printing and cultural and educational sporting goods	34.4346	30.0881	27.2203
Petroleum, coking products, and nuclear fuel processing	271.4136	290.6032	210.0880
Chemical products	199.6707	152.1393	162.7892
Non-metallic mineral products	945.5976	935.2521	953.3806
Metal smelting and calendering	1434.1274	1613.7178	1559.3276
Metalware	15.3569	11.5383	19.0730
Flexible units	35.0204	34.1923	32.3724
Dedicated devices	12.9314	15.5221	18.7256
Transport and communication facilities	25.1383	18.9422	17.4541
Electrical machinery and equipment	11.5931	10.7235	9.5147
Communication equipment, computers and other electronic equipment	6.1912	5.4024	5.2366
Instruments and apparatuses	1.2221	1.1409	0.8796
Other manufacturing	7.7621	6.8013	3.5064
Production and supply of electricity and heat	4741.4246	4690.6059	5070.1765
Gas production and supply	12.9596	16.9220	16.1230
Water production and supply	0.7651	0.6654	0.5356
Architecture	58.3075	63.8286	65.1358
Wholesale and retail, accommodation and catering	155.0949	160.3929	158.6744
Transportation, warehousing and postal services	616.9507	652.4001	705.3659
Other service industries	131.1025	169.2745	156.6213

8. Calculation and Analysis of Embodied Carbon Emissions from Region to Industry

Measurement of Embodied Carbon Emissions

Embodied carbon refers to the carbon dioxide directly or indirectly released in the entire production chain, from raw material acquisition, processing and production, transportation, and storage to sales and use.

In light of the decomposition method of complete commerce proposed by Wang et al. [16], carbon dioxide is decomposed according to its destination in this study. The multi-regional input–output table of China encompasses G provinces and N industrial sectors, where C^s is the CO_2 emissions of N sectors in s province (order 1 × N) and $\hat{f}^s$ is the CO_2 emission coefficient vector (order N × 1), and the meanings of other variables are consistent with those in the domestic value chain measurement method.

The decomposition formula for carbon dioxide emissions at the industrial level of N departments in *s* province is as follows:

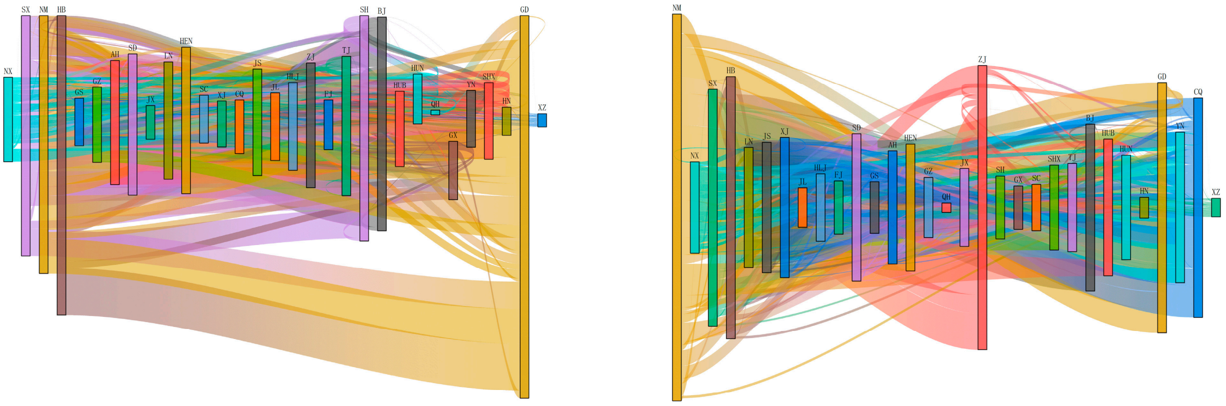
$$C^s = \underbrace{\hat{f}^s L^{ss} Y^{ss}}_{C_1} + \underbrace{\hat{f}^s L^{ss} \sum_{r=1,r\neq s}^{G} Y^{sr}}_{C_2} + \underbrace{\hat{f}^s L^{ss} \sum_{r=1,r\neq s}^{G} A^{sr} L^{rr} Y^{rr}}_{C_3} + \underbrace{\hat{f}^s L^{ss} \sum_{r=1,r\neq s}^{G} A^{sr} \sum_{u=1}^{G} B^{ru} Y^{us}}_{C_4} + \underbrace{\hat{f}^s L^{ss} \left[\sum_{r=1,r\neq s}^{G} \sum_{t=1,t\neq s}^{G} A^{st} \sum_{u=1}^{G} (B^{tu} Y^{ur}) - \sum_{r=1,r\neq s}^{G} A^{sr} L^{rr} Y^{rr} \right]}_{C_5} \quad (6)$$

Formula (6) indicates that carbon dioxide at the national sector level is decomposed into five parts, with specific meanings as follows: C_1 is the CO_2 emissions implied in the local final product demand; C_2 is the CO_2 emissions implied in the final demand exported to other regions; C_3 is the CO_2 emissions implied in intermediate products exported to other regions; C_4 is the CO_2 emissions hidden in intermediate goods exported to other regions and then returned to satisfy local requirements for final products; and C_5 is the CO_2 emissions hidden in intermediate goods and re-exported to other regions by the place of import.

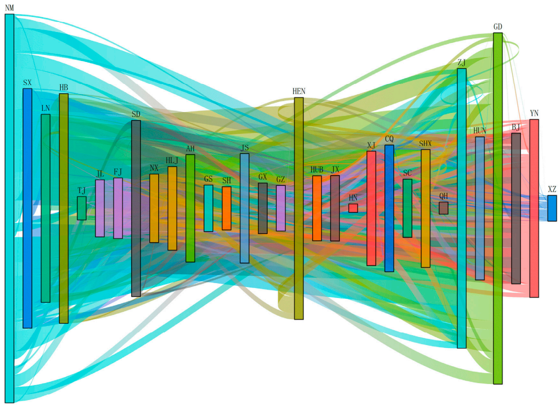
9. Analysis of Hidden Carbon Measurement Results by Province and Industry in China

The results for the hidden carbon calculated by the above method for each province in China are shown in Table 1. The top three implied carbon emissions in 2012, 2015, and 2017 were from Shandong Province, Hebei Province, and Jiangsu Province, respectively. The hidden carbon emissions of Shandong Province rank first in China, due to three main reasons: first, large amounts of pesticides and fertilizers are used in agricultural activities in this province; second, the energy consumption structure of this province caused by economic development and population factors is based on coal; and third, the irrational industrial structure of this province is dominated by heavy industry with low energy utilization efficiency. In 2017, Shandong's carbon emissions increased by −4.46% compared with 2012, indicating that its carbon emissions are declining year by year, and a series of green transformation measures adopted by Shandong Province have achieved remarkable results. As a major carbon-emitting province, Hebei has huge coal-based energy consumption. Despite Hebei's efforts to increase industrial restructuring, heavy industry is still the backbone of Hebei's economic development. Hebei's carbon emissions in 2017 increased by 3.96% compared with 2012, and it is still necessary to implement various carbon emission reduction policies. The carbon emissions of Jiangsu Province in 2017 increased by 15.12% compared with 2012. The possible reason for this is that the carbon emissions of Jiangsu's five major industries, namely steel, petrochemicals, building materials, textiles, and paper, accounted for about three-quarters of its total industrial carbon emissions, and the ratio of its fossil energy to non-fossil energy use was 9:1, which was much higher than the requirement for carbon neutrality, resulting in high carbon emissions in Jiangsu Province. As an extremely rich base of heavy industries such as energy, chemicals, and raw materials, the carbon emissions of Inner Mongolia, Henan, and Shanxi in the middle reaches of the Yellow River should not be underestimated. Hainan, Qinghai, and Beijing have the lowest implied carbon emissions, with Hainan's carbon emissions being about one-twentieth of Shandong's.

In this paper, a Sankey map is used to describe the interregional hidden carbon flow in various provinces of China. The Sankey diagram, as a flow diagram, is composed of nodes and edges connecting nodes, where the width of the edge represents the number of flows, which can intuitively show the flow relationship and quantitative differences among various elements. The colors of the bars in the Sankey diagram represent different provinces and their respective implied carbon flows. As shown in Figure 3, each province is represented as a node, and the lines between the nodes represent the flow of hidden carbon. In 2012, the hidden carbon flow was mainly concentrated in Beijing, Hebei, Guangdong and other economically developed provinces with large energy consumption. As the main sources of hidden carbon, these regions transferred a large amount of hidden carbon to neighboring and inland provinces. However, in 2015, with the national emphasis on energy conservation and emission reduction and the adjustment of energy structure, the pattern of hidden carbon flow changed to some extent, and some provinces in central and western China have become important recipients of hidden carbon, which not only reflects the transformation of regional economic structure, but also reflects the profound reform of energy consumption pattern. By 2017, China's hidden carbon flows showed a diversified and complicated trend. On the one hand, the eastern coastal provinces still maintained a higher hidden carbon output, but the output quantity and direction were more dispersed. On the other hand, the central and western provinces began to form an internal hidden carbon flow network while receiving hidden carbon, which shows the interaction between energy consumption and industrial structure in the process of economic development in these regions. It is worth mentioning that although the hidden carbon flow in remote areas such as Tibet and Qinghai is relatively small, the change in the hidden carbon flow is also worthy of attention under the background of the construction of the national ecological security barrier.



Year 2012 Year 2015



Year 2017

Figure 3. Implied carbon flows by province in China in 2012, 2015, and 2017. Note: The horizontal axis provides the English abbreviation of each province, corresponding to "Beijing" and other provinces in Table 1. The above Sankey diagram was created using Origin 2022 SR1.

The results of China's implied carbon emissions by industry are shown in Table 2. In 2012, 2015, and 2017, the top four industries for implied carbon emissions were the power and heat production and supply industry, the metal smelting and rolling processing industry, the non-metallic mineral products industry, and the transportation, storage and postal industry, accounting for about 50%, 16%, 10%, and 7% of the total carbon emissions of all industries in China, respectively. The carbon emissions of these four sectors in 2017 increased by 6.93%, 8.73%, 0.82%, and 14.33%, respectively, compared with 2012. The reason why the implied carbon emissions for the generation and distribution of heat and electricity are at a high level all year round is that China's electricity production mainly relies on thermal power generation, which is based on the consumption of large amounts of coal, oil, and other energy sources, so it releases a very large amount of CO_2 due to the combustion of fossil fuels. The main activity of the metal smelting and rolling processing industry is smelting steel, and its raw materials are mainly coal and coke, so the carbon emissions of this industry are also high. The non-metallic mineral products industry is mainly based on the production of cement, lime, and other building materials, and its carbon emissions have been high for a long time due to the consumption of fossil fuels in the production process with the use of equipment. The transport, warehousing, and postal sectors have increased carbon emissions due to the increasing convenience and power of transport and the need to burn fossil fuels to release energy. The coal mining products industry and the petroleum, coking products, and nuclear fuel processing industry have lower carbon emissions than the above four industries, but their carbon dioxide emissions cannot be ignored. The hidden carbon emissions of the remaining 23 industries are in a relatively normal and stable state, and the percentage of hidden carbon emissions of these 23 industries in 2012, 2015, and 2017 was about 10.5% of the total emissions in each year, or about one-fifth of the production and supply of electricity and heat.

10. Empirical Testing of the Effect of the Embeddedness of National Value Chains on Embodied Carbon Emissions

10.1. Action Effect Analysis and Research Hypothesis

The Suppressing Effect of National Value Chain Embeddedness on Embodied Carbon Emissions

Climate change is a serious challenge facing the whole world. In recent times, in order to realize its dual-carbon target on schedule, the Chinese government has dedicated itself to formulating and implementing a series of carbon emission reduction policies, and developing and optimizing domestic value chains is one of the powerful means to achieve this. Chen et al. found that domestic value chain embedding has a significant inhibitory effect on energy efficiency [17]. National value chains are complete industrial chains based on national market demand, from design and development, raw material acquisition, transportation, and storage to sales and use. The embeddedness of domestic value chains has notably promoted the allocation and circulation of resources in various regions, promoted the integration of all regions into the internal market's division of labor system, and smoothed the circulation of the domestic economy. Such economic integration not only enables participants to gain advanced management experience and technical means, but also enables them to familiarize themselves with the domestic market and environmental standards as soon as possible. It is necessary to accelerate local green technology innovation and improvement of the industrial structure, enhance the market competitiveness of local enterprises, improve local environmental pollution, improve energy efficiency, and reduce hidden carbon emissions.

Hypothesis 1: *National value chain embeddedness has an inhibitory effect on embodied carbon emissions.*

11. Industrially Heterogenous Effects of National Value Chain Embeddings on Embodied Carbon Emissions

Domestic industries participate in the domestic economic cycle in different ways according to the advantages of regional resource endowments, and industries with excellent geographical locations or rich resources participate in more diversified, more technologically advanced, and higher value-added upstream links. The traditional industries that are located in remote areas and lack resources mainly participate in the downstream links of low value-added processing, manufacturing, and low-end technical services. These industries not only bear environmental pressure, but also their economic development is stagnant. Chen et al. found through heterogeneity tests that the inhibition effect of domestic value chain embedding on energy efficiency is more prominent in low-polluting and high-tech industries [17]. Chen and Li [12] found through the analysis of industry and inter-industry heterogeneity that the division of labor within a single industry is not conducive to the construction of a complete industrial chain system, and cross-industry division has a significant effect on the "carbon synergy" effect of the vertical division of labor path of domestic value chains. This also shows that high-tech industries, through their technological advantages in researching and designing more low-carbon and clean products, decrease their carbon emissions concurrently. The level of science and technology is far ahead in these industries. Meanwhile, in low-tech industries, carbon emissions cannot be underestimated; coupled with the lack of technical support for carbon emission reduction, these industries become a high-carbon-emission area, and the inertia of technological innovation leads to a vicious circle. Due to their excessive energy consumption, high-energy-consumption industries may be forced to speed up the process of green transformation and upgrading under market and policy pressure so as to lower their carbon dioxide emissions. Low-energy-consumption industries have low energy consumption, and it is easier to optimize the energy structure and upgrade the industrial structure of these industries than those of high-energy-consumption industries, so their carbon emissions are also decreasing.

Hypothesis 2: *Domestic value chain embeddedness has industrially heterogenous effects on hidden carbon emissions in terms of technology category and energy consumption.*

12. Specification of Model

In order to look into how each province's implied carbon footprint is affected by the level of embeddedness in the domestic value chain, the following measurement model is set out in this paper:

$$CO2_{it} = \alpha + \beta_1 NVC_{it} + \beta_2 Z_{it} + \delta_{it} + \nu_{it} + \varepsilon_{it} \tag{7}$$

In Equation (7), $CO2_{it}$ represents the implied carbon emissions of province i in year t, NVC_{it} represents the level of domestic value chain embeddedness of each province in the corresponding year, α is a constant term, Z_{it} is the collection of control variables, β_1 and β_2 are the main explanatory variables and the set coefficients of control variables, δ_{it} and ν_{it} represent individual and time-fixed effects, respectively, and ε_{it} is a random error term.

13. Variable Construction

Explained variable: The embodied carbon emissions (CO_2) of each province, representing the carbon dioxide emissions in the process of economic and trade exchanges and cooperation between provinces.

Core explanatory variable: The degree of national value chain embeddedness (*NVC*) of each province, which is calculated based on the ratio of the degree of forward and backward embeddedness in the national value chain, reflecting the position of each economy in the national value chains.

Control variables: (1) Energy structure (*ES*): At present, domestic energy consumption mainly relies on coal resources, and the use of coal is directly proportional to the $\mathrm{CO_2}$ emissions resulting from it. Therefore, the energy structure is calculated using the ratio of total energy consumption to total raw coal consumption. (2) Technological innovation (*PAT*): Technological innovation is conducive to improving the regional energy consumption structure and promoting the industry to accelerate the country's green transformation, so the number of patents for inventions is used as a measure. (3) Industrial structure upgrading (*IndSA*): Reflects the difference in industrial structure between provinces, using the ratio of tertiary industry to secondary industry as a measure. (4) Output per capita (*OutPA*): Reflects the economic development of each region, using the ratio of regional GDP to the number of people in employment as a measure. (5) Inter-provincial infrastructure (*InfraS*): The total mileage of roads in each province is measured. (6) Capital deepening degree (*CapDep*): The increase in capital stock is conducive to improving industrial production efficiency, expediting industrial green transformation, and promoting the coordinated development of pollution reduction and carbon reduction. Each province's capital stock is estimated using the perpetual inventory approach, and the calculation formula is as follows:

$$K_{it} = I_{it} + (1 - \sigma) K_{i,t-1} \tag{8}$$

In Formula (8), K_{it} is the capital stock of the first year of the province; I_{it} is the first annual fixed asset investment of the first province; and with reference to Zhang et al. [18], the depreciation rate σ is 9.6%.

The formula for calculating the base period capital stock is

$$K_{i,2012} = I_{i,2012}/(g_{2012} + \sigma) \tag{9}$$

In Formula (9), g_{2012} is the average growth rate of fixed assets of each province in 2012. The initial fixed asset investment data are composed of the sum of the net production tax, the depreciation of fixed assets, and the operating surplus in China's multiregional input–output table. The extent of capital deepening is measured by the ratio of capital stock to the number of employees in each province.

14. Data

This study's primary data came from China's carbon accounting database (CEAD), which includes carbon dioxide emissions data for 2012, 2015, and 2017, and China's multi-regional input–output table, which quantifies the degree of embeddedness of domestic value chains. China's multi-regional input–output tables are complicated to compile, and the latest available data are for 2017, However, in 2013, 2014, and 2016, the table was not prepared and updated in a timely manner. We selected China's multi-regional input–output tables and carbon emission data in 2012, 2015, and 2017 for research, mainly based on data availability and timeliness. At present, the latest and most comprehensive data of China's multi-regional input–output table are the data of these three years; 2012 and 2015 are in the middle and early stages of the 12th Five-Year Plan, respectively, and 2017 is in the early stages of the 13th Five-Year Plan. They can better reflect the changing trend of China's economic structure, industrial layout, and carbon emission characteristics. At the same time, this period is also a critical period for the Chinese government to introduce a series of climate change policies. Studying these data will help to evaluate the effect of policies and provide an important basis for formulating more scientific carbon reduction strategies. The research scope of this paper covered 31 provinces in China. Since the CEAD lacks CO_2 emission data for Tibet, these data were calculated as follows: CO_2 emission of various industries in Tibet = CO_2 emission coefficient of each industry in Tibet × total input of each industry in Tibet, where the CO_2 emission coefficient of each industry in Tibet is assumed to be equal to the CO_2 emission coefficient of different industries in China, that is, the CO_2 emissions of different industries in China divided by the total input of corresponding industries. Since the industry types in the multi-regional input–output table and CO_2 emission table are not uniform, they were adjusted to a total of 29 industries according to the unchanged common industries and the merger of non-common industries as needed. Other variable data were obtained from the China Statistical Yearbook, the China Energy Statistical Yearbook, the China Population and Employment Statistical Yearbook, the China Labor Statistics Yearbook, and the provincial statistical yearbook for each corresponding year.

15. Empirical Analysis

Benchmark Regression

In this paper, empirical tests are carried out through the above econometric model, and the regression results are shown in Table 3. Table 3 reflects estimates of the level of embeddedness in national value chains and the embodied carbon emissions by province in China, with all regression results controlling for fixed effects by province and year. In this table, column (1) provides the regression results based on the primary explanatory variables and the explained factors. It shows that the degree of domestic value chain embeddedness is significantly negative at the level of 1%, that is, every 1 unit increase in the degree of domestic value chain embeddedness reduces carbon emissions by 0.294 units, indicating that with the deepening of the degree of domestic value chain embeddedness, CO_2 emissions in each province show a decreasing trend. In short, the deepening of NVC embeddedness can improve the inter-provincial trade and environment imbalance, and Hypothesis 1 is verified.

Table 3. Influence of embeddedness of domestic value chain on embodied carbon emissions.

Variable	(1) FE	(2) FE	(3) FE	(4) FE	(5) FE
NVC	−0.294 **	−0.267 *	−0.278 *	−0.331 **	−0.332 **
	(−2.11)	(−1.72)	(−1.76)	(−2.02)	(−2.01)
ES		2.818 ***	2.755 ***	2.572 ***	2.535 ***
		(3.52)	(3.38)	(3.11)	(3.03)
PAT		0.000 **	0.000 **	0.000 **	0.000 **
		(2.07)	(2.11)	(2.04)	(2.09)
IndSA		−0.191	−0.244	−0.315	−0.327
		(−1.17)	(−1.24)	(−1.53)	(−1.57)
lnOutPA			−0.174	−0.192	−0.173
			(−0.50)	(−0.55)	(−0.49)
InfraS				−0.000	−0.000
				(−1.16)	(−1.21)
CapDep					−0.002
					(−0.51)
Cons	0.918 ***	1.473 **	1.923 *	2.852 **	2.922 **
	(23.35)	(2.60)	(1.80)	(2.14)	(2.16)
Province effect	YES	YES	YES	YES	YES
Year effect	YES	YES	YES	YES	YES
N	90	93	93	93	93
R2	0.005	0.297	0.300	0.317	0.321

Note: ***, **, and * represent the T-values estimated by the coefficients at the significance levels of 1%, 5%, and 10%, respectively. Source: Calculated by StataMP 17 software.

Based on domestic demand, domestic value chains, as orderly and stable regional division of labor networks, enable the provinces to deepen trade cooperation in "endogenous" links such as factor supply, research and development design, parts production, finished product assembly, and logistics distribution, encouraging industries to achieve green and low-carbon environmental protection goals as soon as possible. Columns (2), (3), (4), and (5) report the results of regression after adding three, four, five, and six control variables, respectively. With the gradual increase in control variables, although the coefficient of NVC fluctuates, it always remains in the negative range, and the significance level is stable. It is worth noting that the absolute value of the NVC coefficient increases slightly in columns (4) and (5), reaching −0.331 and −0.332, respectively, indicating that the negative effect of NVC embedding on carbon emissions becomes more significant after more factors that may affect carbon emissions are considered. This reveals that the deepening of the embeddedness of the domestic value chain promotes provinces to migrate upstream in the value chain system, which is characterized by strengthening the intermediate product supply chain with technological innovation as the core. This trend not only leads the provinces to gradually get rid of the traditional production mode of high energy consumption and low added value, but also reduces the excessive dependence on high-tech products in developed provinces, thus avoiding the risk of falling into the trap of high carbon emissions due to technical bottlenecks. This transformation is of great significance for promoting substantial energy conservation and emission reduction, and promoting a sustainable development model that benefits both the economy and the environment. In addition, we observe that the R^2 value of the model gradually increases with the increase in the control variables, from 0.005 to 0.321, indicating that the goodness of fit of the model is improving, and the explanatory variables are gradually explaining the explained variables.

16. Robustness Test

The aforementioned study examined how a domestic value chain's embeddedness affects embodied carbon emissions. To ensure the reliability, stability, and consistency of the conclusions, we examined the methods for swapping out the main explanatory variables, replacing the explanatory variables, and adding control variables to examine the robustness of the regression results.

(1) Replace core explanatory variables

Based on the calculation method provided by Lai et al. [9], in this paper, we re-measure the level of embeddedness in the national value chain—that is, the participation in the internal value chain. The specific formula is as follows:

$$NVCP = NVCf + NVCb \tag{10}$$

The regression results are displayed in Table 4's column (1), which shows that after replacing the core explanatory variables, the degree of embeddedness in the domestic value chain is still negatively correlated with the implied carbon emissions, indicating that the conclusion is stable.

Table 4. Robustness test.

Variable	(1) FE	(2) FE	(3) FE
NVCP	−0.566 **	−0.334 *	−0.339 *
	(−2.02)	(−1.91)	(−1.97)
Control variable	YES	YES	YES
Urban			−0.452
			(−0.15)
Province effect	YES	YES	YES
Year effect	YES	YES	YES
N	93	93	93
R^2	0.204	0.335	0.321

Note: ** and * represent the T-values estimated by the coefficients at the significance levels of 5%, and 10%, respectively.

(2) Replace the explained variable

The decomposed and calculated implied carbon emissions were replaced with carbon emission data in the carbon emission CEAD, and the robustness test results are shown in column (2) of Table 4. The findings indicate a negative effect of the embeddedness level of the national value chain on concealed carbon emissions.

(3) Increase control variables

Considering that there might be missing variables in the model, a new control variable, inter-provincial urbanization level (*Urban*), was added, calculated as the proportion of the urban population within the total population at the end of the year. The regression results are shown in column (3) of Table 4, and the findings demonstrate that the basic conclusions of this study are still valid.

17. Endogeneity Test

The endogeneity problem will lead to biased and inconsistent estimation results; thus, in this paper, we adopt the lag instrumental variable strategy to solve the endogeneity problem. The Hausmann test findings show that, at a significance level of 1%, the null hypothesis that the "explanatory variable is an exogenous variable" may be rejected, meaning that the embeddedness of the domestic value chain is an endogenous variable. Table 5 reports the results of fixed-effect regression using endogenous variables with a one-stage lag as instrumental variables. It can be demonstrated from the estimation results that the coefficients of explanatory variables are significantly negative at the levels of 1% and 5%, respectively, when control variables are included and when they are not. As can be seen from the test results of the weak correlation hypothesis for instrumental variables, the minimum eigenvalue statistic is greater than 10. As a result, the conclusion of this work remains true because there is no weak instrumental variable issue.

Table 5. Endogeneity test.

Variable	**(1)** **FE**	**(2)** **FE**
NVC	−0.041 ***	−0.055 **
	(−8.32)	(−2.94)
Control variable	NO	YES
Province effect	YES	YES
Year effect	YES	YES
N	62	62
R^2	0.999	0.999

Note: *** and ** represent the Z-values estimated for the coefficients at the significance level of 1%, and 5%, respectively.

18. Heterogeneity Analysis of Industry

The degree of embeddedness of domestic value chains has an industrially heterogenous impact on implicit carbon emissions. According to the WIOD classification standard, industries are divided into two categories: high technology and low technology. Among them, high-technology industries include the chemical products industry, the general equipment industry, the special equipment industry, the transportation equipment industry, the electrical machinery and equipment industry, the communication equipment industry, and the computer and other electronic equipment and instrumentation industry. Low-tech industries comprise the remaining 22 industries. At the same time, according to the “People’s Republic of China 2016 National Economic and Social Development Statistical Communique” issued by the National Bureau of Statistics, industries can be classified by energy consumption. Among them, the high-energy-consumption industries are the petroleum, coking products, and nuclear fuel processing industry; the chemical products industry; the non-metallic mineral products industry; the metal smelting and rolling processing industry; the electricity, heat production, and supply industry; and the transportation, storage, and postal industry. Low-energy industries include the remaining 23 industries.

Column (1) in Table 6 displays the regression findings of the effect of embeddedness in a domestic value chain on implicit carbon emissions across all 29 industries. The findings essentially confirm the aforementioned conclusions, demonstrating that the effects of NVC embeddedness on CO_2 emissions are notably negative at the 5% level. It can be seen that the degree of NVC embeddedness determines, to a certain extent, whether domestic industries can better produce, use, and reuse raw materials and products, whether they can effectively reduce the large volume of CO_2 emissions produced throughout the entire life cycle of product research and development, design, production and processing, sales and consumption, and recycling, and whether they can significantly contribute to achieving the goals of pollution reduction and carbon emission reduction.

Table 6. Industrial heterogeneity test of the impact of embeddedness of domestic value chain on embodied carbon emissions.

Variable	**(1)** **All Sectors**	**(2)** **High Technology**	**(3)** **Low Technology**	**(4)** **High Energy Consumption**	**(5)** **Low Energy Consumption**
lnNVC	−3.971 **	−3.926 *	1.522 **	−44.567 *	−3.621 **
	(−2.03)	(−1.92)	(2.09)	(−2.01)	(−2.11)
Controlvariable	YES	YES	YES	YES	YES
Industry effect	YES	YES	0.388	YES	YES
Year effect	YES	YES	YES	YES	YES
N	87	21	66	18	69
R^2	0.540	0.954	22	0.937	0.518

Note: ** and * represent the T-values estimated by the coefficients at the significance levels of 5%, and 10%, respectively.

Columns (2) and (3) in Table 6 show the regression results of both low-tech and high-tech industries. The results show that the relationship between the degree of NVC embedding and carbon emissions in high-tech industries is significantly negative, while the coefficient of NVC embedding degree in low-tech industries is significantly positive. The possible reasons for this are as follows: high-tech industries mainly provide intermediate products to other industries by virtue of their technological advantages, and their product research and development and scientific and technological innovation capabilities are at an industry-leading level, which is effective for carbon emission reduction. Low-tech industries are limited to the downstream processing and assembly links of the value chain with low added value and high carbon emissions, mainly relying on traditional factor-intensive industries, which increase carbon emissions. Simultaneously, due to the lack of scientific and technological competitiveness, the impact of cheap and high-quality products in high-tech industries is more limited by low-carbon technology research and development capital, ability, and enthusiasm, thus creating a high-carbon-emission zone.

Columns (4) and (5) in Table 6 show the regression results of high- and low-energy-consumption industries. The results are similar to those of all industry sample groups and show that the influence of the NVC embedding degree on carbon emissions is notably negative at the levels of 10% and 5%, respectively, in high- and low-energy-consumption businesses. It is evident that the NVC embedding degree has a greater effect on lowering carbon emissions in high-energy-consumption sectors, as the coefficient of the NVC embedding degree grows in these sectors and has a value approximately 12 times higher than in low-energy-consumption industries. This phenomenon may be caused by the large aggregate energy consumption of energy-intensive industries, which leads to a continuous rise in CO_2 emissions from the burning of coal, oil, and other resources. This makes it difficult to meet the current domestic green, low-carbon environmental protection requirements, forcing these industries to invest more in technological innovation and actively drive the main body of the division of labor to improve energy efficiency and innovate regarding low-carbon production technology. This will enable energy-intensive industries to move up the value chain gradually, thereby reducing implicit carbon emissions. Thus, hypothesis 2 is confirmed.

19. Conclusions and Suggestions

Conclusions

Drawing from China's multi-regional input–output tables and carbon emission data for 2012, 2015, and 2017, in this paper, we use the value chain and total trade decomposition methods to calculate the forward and backward embeddedness of the national value chain and the decomposition of embodied carbon emissions, and empirically investigate the effect of the embeddedness of the domestic value chain on the implicit carbon emissions by using the measurement results. The main conclusions can be summed up as follows:

(1) The value chain measurement method is used to disaggregate and calculate the added value and final goods of 31 provinces and 29 industries in China according to their destination. The degree of forward and backward domestic value chain embeddedness in Chinese provinces increased to varying degrees in 2012, 2015, and 2017, and the degree of forward embeddedness in most provinces was lower than the degree of backward embeddedness, indicating that the degree of all-round embeddedness in domestic value chains from both forward and backward perspectives has been deepening. However, backward embedding is still dominant, which represents segments with little added value, such as processing, manufacturing, and assembly. It is found that industries with a high degree of forward and backward embeddedness are mainly concentrated in the oil and gas mining industry, coal mining product industry, and metal mining product industry in the manufacturing sector, and the backward embeddedness of the national value chain in each industry is significantly higher than the forward embeddedness. This shows that most industries are still at the bottom of the value chain.

(2) The total trade decomposition method is used to estimate the implied carbon emissions of 31 provinces and 29 industries in China. In 2012, 2015, and 2017, Shandong, Hebei, and Jiangsu consistently featured among the top three provinces with the highest levels of embodied carbon emissions, which were mostly brought on by the heavy-industry-dominated industrial structure, the energy consumption structure being biased towards coal, an insufficient impetus for scientific and technological innovation, and geographical location restrictions. At the same time, the implied carbon emissions in the middle reaches of the Yellow River should not be underestimated, and the lowest indicated carbon emissions were found in Beijing, Qinghai, and Hainan. The top four industries in terms of annual implied carbon emissions are the electricity and heat generation and supply industry; the metal smelting and rolling industry; the non-metallic mineral products industry; and the transportation, storage, and postal industry. The reason for the high carbon emissions in these industries is mainly their large-scale use of various fossil fuels. In particular, many industries are deeply dependent on coal, oil, and other energy sources.

(3) The fixed-effect regression approach was used to empirically analyze the impact of the degree of embeddedness of the domestic value chain on implicit carbon emissions. Excluding or incorporating diverse control variables, a negative relationship is observed between the embeddedness of national value chains and implied carbon emissions, suggesting that enhancing the integration of national value chains can mitigate inter-provincial trade-related environmental disparities and expedite industries' progress towards green and low-carbon development goals. To ascertain the credibility and consistency of this conclusion, the robustness of the regression outcomes was verified through substitution of the primary explanatory variable, alternation of the dependent variable, and augmentation of control variables. At the same time, the explanatory variable was used as an instrumental variable to test its endogeneity by means of fixed-effect regression, and the conclusion was still valid.

(4) There is industrial heterogeneity in the effect of the embeddedness of domestic value chains on implicit carbon emissions. The industries are separated into industries with high and low technology levels according to technology categories and industries with high energy consumption and low energy consumption according to energy consumption. The regression analysis indicates that the level of embeddedness within the value chains of China, encompassing all 29 industries, exerts a markedly negative influence on embodied carbon emissions, reaching statistical significance at the 5% threshold. There is a strong negative link between carbon emissions and the level of NVC embeddedness in high-tech industries, while the coefficient of NVC embeddedness in low-tech industries is significantly positive. One plausible explanation for this could be that low-tech sectors are restricted to the value chain's downstream processing and assembly links, which have poor added value and large carbon emissions, and the lack of scientific and technological competitiveness leads to a vicious circle of carbon emissions. The extent of NVC embeddedness in both high- and low-energy-consuming sectors displays an inverse relationship with carbon emissions.

20. Suggestions

(1) Targeted construction and optimization of regional and industrial domestic value chains: In view of the current situation of unbalanced regional development in China, especially the significant differences between coastal and inland, and developed and underdeveloped regions, it is recommended to adopt more refined strategies to promote the construction and optimization of domestic value chains. Specifically, for provinces with higher implied carbon emissions, such as Shandong, Hebei, and Jiangsu, emphasis should be placed on optimizing the industrial structure, reducing the proportion of heavy industry, and taking advantage of their position in the value chain to guide their transformation to higher value-added industrial chain links. For the middle Yellow River region, cooperation within the region should be strengthened to reduce hidden carbon emissions through technology introduction and industrial upgrading. In addition, in the manufacturing sector, industries such as oil and gas mining, coal mining products, metal mining, and other

highly embedded and carbon-intensive industries should be promoted to change to a green and low-carbon production mode, and use technological innovation to improve resource utilization efficiency and reduce environmental pollution.

(2) Tap the potential of domestic demand and promote the integration of regional resources: Based on the huge potential of China's consumer market, all regions should deeply tap their own unique resources, such as tourism resources in Hainan and clean energy resources in Qinghai, and promote the optimal allocation and efficient use of these resources through policy guidance and market mechanisms. For regions with low implied carbon emissions such as Hainan, their ecological advantages should be further utilized to develop low-carbon industries such as green tourism and ecological agriculture. At the same time, other regions should be encouraged to learn from their green development experience and form regional development models with their own characteristics and mutual benefits. In addition, high-carbon emission industries such as electricity, heat production and supply, and metal smelting should be encouraged to use clean energy to replace traditional fossil fuels and reduce carbon emissions.

(3) Pay equal attention to government guidance and market regulation to promote industrial green transformation: The government should formulate differentiated energy conservation and emission reduction policies according to the characteristics of different industries. For high-tech industries, we should continue to increase investment in scientific research, encourage technological innovation, and improve their position in the domestic value chain. At the same time, tax incentives, financial support, and other means should be used to promote their transformation to a greener and low-carbon production mode. Low-technology, high-energy industries, such as non-metallic mineral products, transportation, and other industries, should be forced to carry out technological transformation and industrial upgrading through strict environmental supervision and emission standards, and reduce carbon emissions. At the same time, the government should give full play to the role of the market mechanism and guide the flow of production factors to green and low-carbon industries through price leverage, market competition, and other means to achieve efficient allocation of resources and sustainable economic development.

(4) Scientific and technological innovation leads the energy revolution and achieves synergies: In view of the current situation of China's energy structure biased toward coal, high energy consumption, and large carbon emissions, the pace of scientific and technological innovation should be accelerated to promote fundamental changes in energy production and consumption methods. Specifically, we should increase the research and development and application of clean energy technologies, such as solar energy, wind energy, nuclear energy, etc., and reduce the dependence on traditional fossil fuels such as coal and oil. At the same time, enterprises are encouraged to adopt advanced energy-saving and emission-reduction technologies and equipment to improve energy efficiency and reduce carbon emissions. Industries with high carbon emissions, such as electricity and heat production and supply, should be a key area of scientific and technological innovation and energy revolution, and achieve synergies in energy conservation, carbon reduction, and pollution reduction through technological innovation and industrial upgrading. In addition, we should strengthen international cooperation and exchanges, learn from international advanced experience and technological achievements, and jointly address the challenge of global climate change.

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References

1. Ji, X.; Liu, Y.; Wu, G.; Su, P.; Ye, Z.; Feng, K. Global value chain participation and trade-induced energy inequality. *Energy Econ.* **2022**, *112*, 106175. [CrossRef]
2. Jithin, P.; Ashraf, S. Global value chain participation and CO_2 emissions: Does economic growth matter? New evidence from dynamic panel threshold regression. *Energy Econ.* **2023**, *128*, 107154. [CrossRef]
3. Lv, Y.; Cui, X.; Wang, D. GVC Participation and Carbon Embodied in international Trade: Nonlinear Analysis Based on GMRIO and PSTR Model. *J. Quant. Tech. Econ.* **2019**, *36*, 45–65. (In Chinese) [CrossRef]
4. Zheng, L.; Zhao, Y.; Shi, Q.; Qian, Z.; Wang, S.; Zhu, J. Global value chains participation and carbon emissions embodied in exports of China: Perspective of firm heterogeneity. *Sci. Total Environ.* **2022**, *813*, 152587. [CrossRef] [PubMed]
5. Zhang, B.; Ning, Y.; Bai, S. Reassessing the embodied carbon emissions in China's foreign trade: A new perspective from the export routes based on the global value chain. *Environ. Sci. Pollut. Res.* **2023**, *30*, 31348–31369. [CrossRef] [PubMed]
6. Guo, X.; Huang, K.; Li, L.; Wang, X. Renewable energy for balancing carbon emissions and reducing carbon transfer under global value chains: A way forward. *Sustainability* **2022**, *15*, 234. [CrossRef]
7. Wang, J.; Rickman, D.; Yu, Y. Dynamics between global value chain participation, CO_2 emissions, and economic growth: Evidence from a panel vector autoregression model. *Energy Econ.* **2022**, *109*, 105965. [CrossRef]
8. Qian, Z.; Zhao, Y.; Shi, Q.; Zheng, L.; Wang, S.; Zhu, J. Global value chains participation and CO_2 emissions in RCEP countries. *J. Clean. Prod.* **2022**, *332*, 130070. [CrossRef]
9. Lai, X.; Tang, Y.; Zhu, S. Environmental Kuznets effect of countries' participation in global value chains: Based on multinational panel data. *Resour. Sci.* **2022**, *44*, 1630–1644. (In Chinese)
10. Zhu, S.; Tang, Y.; Qiao, X.; You, W.; Peng, C. Spatial effects of participation in global value chains on CO_2 emissions: A global spillover perspective. *Emerg. Mark. Financ. Trade* **2022**, *58*, 776–789. [CrossRef]
11. Sun, Z.; Sun, Y.; Liu, H.; Cheng, X. Impact of spatial imbalance of green technological innovation and industrial structure upgradation on the urban carbon emission efficiency gap. *Stoch. Environ. Res. Risk Assess.* **2023**, *37*, 2305–2325. [CrossRef]
12. Chen, Z.; Li, H. Domestic value chain production division network and provincial-industry carbon emission intensity gap: Narrowing or widening. *Macroecon. Res.* **2022**, *11*, 104–121. (In Chinese) [CrossRef]
13. Bai, S.; Ning, Y.; Zhang, B. Estimating the environmental and employment impacts of China's value-added trade from the perspective of value chain routes. *Environ. Sci. Pollut. Res.* **2022**, *29*, 73414–73443. [CrossRef] [PubMed]
14. Shen, J.Y. *Research on the Measurement of Carbon Implicit in China's Foreign Trade From the Perspective of Added Value*; Jiangxi University of Finance and Economics: Nanchang, China, 2023. (In Chinese)
15. Wang, Z.; Wei, S.; Yu, X.; Zhu, K. *Measures of Participation in Global Value Chains and Global Business Cycles*; Working Paper; National Bureau of Economic Research: Cambridge, MA, USA, 2017.
16. Wang, Z.; Wei, S.J.; Zhu, K.F. Total trade accounting method: Official Trade statistics and measurement of global value Chains. *Soc. Sci. China* **2015**, *108–127*, 205–206. (In Chinese)
17. Chen, G.; Li, B.; Cheng, S. Domestic Value Chain Circulation and Energy Efficiency. *Contemp. Financ.* **2023**, 106–118. (In Chinese) [CrossRef]
18. Zhang, J.; Wu, G.; Zhang, J. The Estimation of China's provincial capital stock: 1952–2000. *Econ. Res. J.* **2004**, *10*, 35–44. (In Chinese)